Studies of Black Holes with masses ~1-1000 M_{sun} with the Constellation-X Observatory

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In addition to enabling new studies of supermassive black holes, Constellation-X will have unique capabilities for studying the stellar-mass black holes residing in binary systems in our own Milk Way and nearby galaxies. These objects become X-ray bright when matter is transferred to the black hole from its binary companion. A number of unique features make these black holes key sources for probing Einstein's theory of General Relativity. 1) These objects represent the nearest and X-ray brightest black holes which Constellation-X can study, and they are also the black holes about which we already know the most (McClintock & Remillard 2004). 2) Many of these systems have been extensively observed at optical and other wavelengths and their masses have been measured with good precision using the methods of dynamical astronomy. With precise mass measurements it becomes easier to constrain the other parameter which describes a black hole's structure, its spin. 3) These are the only black holes known which reveal both X-ray spectroscopic and timing signatures of matter moving in the curved space-time near the event horizon. Constellation-X will be the first X-ray observatory with the capability to study both of these strong gravity signatures simultaneously.

Recent X-ray observations have shown that stellar-mass black holes are similar to their supermassive cousins in that they also show broad, relativistic Fe-K emission lines (Miller et al. 2002, in 't Zand et al. 2002, Miniutti, Fabian & Miller 2004; Miller et al. 2004). The line profiles can be very similar to those seen from the supermassive black holes, indicating that, as in the Seyfert AGNs, they are likely produced in the innermost accretion flow near the black hole. Because these objects are bright, Constellation-X will be able to measure their relativistic line profiles with exquisite precision. Comparisons between lines detected in a number of stellar-mass black holes and Seyfert AGN will test the relative importance of mass accretion versus black hole formation in driving spin.

Observations of some of these same black hole binaries with NASA's Rossi X-ray Timing Explorer (RXTE) resulted in the discovery of high frequency quasi-periodic intensity oscillations (QPOs) with frequencies as high as 450 Hz (Remillard et al. 1999; Strohmayer 2001). These QPOs are the highest frequency flux variations seen from any black holes, and have frequencies characteristic of the orbital timescale near the event horizon. Four of these objects show a pair of QPOs with frequencies in a 3:2 ratio, which could be direct evidence of a resonance phenomenon associated with General Relativistic effects near the black hole (Abramowicz & Kluzniak 2001; Remillard et al. 2002). Interestingly, very recent work on the Galactic microquasar GRS 1915+105 using RXTE suggests that the strength of the broad Fe-K line and the phase of maximum intensity of a lower frequency (1 – 2 Hz) QPO are correlated (Miller & Homan 2005). This suggests that simultaneous X-ray spectroscopy and fast timing measurements can provide new diagnostics of the space-time in the immediate vicinity of these black holes, particularly if Constellation-X can find a direct link between properties of the relativistic Fe-K line and the high frequency QPOs.

The reason that new insights are likely in this regard is that the presence of two different diagnostics provides additional information to enable determination of both the radial location of the X-ray emitting matter and its orbital frequency. If, for example, the black hole mass is known from optical observations, and the spin can be constrained using the observed relativistic line profile, then measurements of QPO frequencies could be used to test whether the orbital frequency at that radius is in agreement with the value predicted by General Relativity. Although such inferences require an understanding of the QPO production mechanism and this problem may not be fully solved by the time Constellation-X flies, the new data provided by Constellation-X will, at a minimum, greatly increase our understanding of how both the relativistic lines and QPOs are generated, and thus bring us closer to the goal of using them as fundamental probes of strong gravity.

The high frequency QPOs are generally weak (approximately 5% of the total variability), and their strength increases with photon energy, so that a combination of large X-ray collecting area above 4 keV and fast timing capability is required to study them. To detect modulations at the highest frequencies observed so far (450 Hz) would require temporal resolution of at least 500 microseconds and preferably 200 microseconds. Both the TES calorimeters and the CdZnTe HXT focal plane array should be able to meet this goal.

A New Class of Intermediate Mass Black Holes:

Constellation-X may be able to crack one of the most intriguing mysteries confronting astronomers presently. The puzzle concerns the nature of a class of luminous, variable, point-like X-ray sources found in many nearby galaxies. Their observed variability confirms that they are compact objects, but they can have inferred isotropic luminosities hundreds of times larger than the expected maximum luminosity of a stellar mass black hole. This has led to speculation that these ultraluminous X-ray sources (ULX) may form a new class of black holes with masses in the range from about 100 - 2000 solar masses, so called intermediate-mass black holes (IMBH, Colbert & Mushotzky 1999). Because these objects are in external galaxies it has not yet been possible to determine their masses with the same methods used to weigh Galactic black holes. Alternative models not requiring excessive masses have also been proposed, generally requiring that the observed X-ray emission is beamed (King et al. 2001). It is imperative that astronomers clearly establish the existence or absence of intermediate-mass black holes: a population of intermediate-mass black holes may have profoundly affected early galaxy evolution (Madau & Rees 2001), and/or may affect the evolution of stellar clusters within galaxies (Miller & Hamilton 2002, Portegies-Zwart et al. 2004).

Constellation-X will improve our understanding of these enigmatic objects in several ways. For example, X-ray timing measurements can identify the characteristic timescales on which the objects are variable. By comparing studies of supermassive black holes with those of stellar mass black holes in our Galaxy, it has been shown that the characteristic variability times scale with black hole mass (Markowitz et al. 2003). The characteristic timescales may be evident either as breaks or QPOs in the power density spectrum. Indeed, recent work using XMM-Newton has led to the first detection of characteristic timescales in ULXs (Strohmayer & Mushotzky 2003; Cropper et al. 2004). The most compelling mass limits would come from sources for which more than one timing signature can be measured in the power spectrum. Exciting possibilities are that both a break in the power-law slope and a single QPO are detected, or that two (or more) QPOs are detected with or without a break. Indeed, if the pairs of 3:2 frequency ratio QPOs seen in Galactic systems are also present in truly more massive ULXs, then they would be expected to appear in the 1 - 10 Hz band (Abramowicz et al. 2004), and if found would convincingly establish at least some ULXs as IMBHs. Only Constellation-X will have the large collecting area necessary to obtain high quality power spectra to search for such signatures.

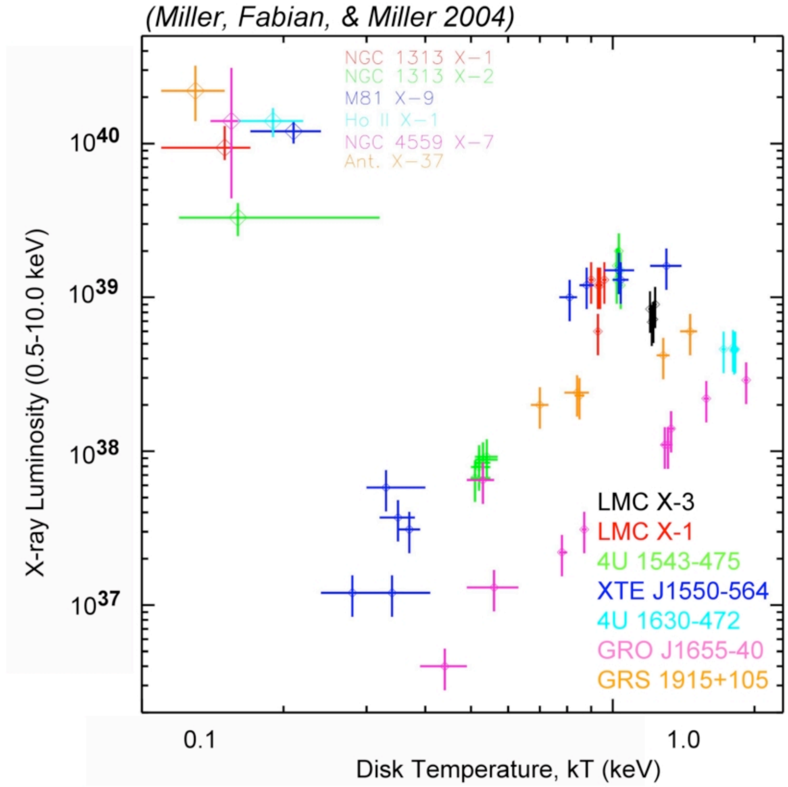

Figure 1: The figure above shows black hole X-ray luminosity versus implied accretion disk temperature, for a number of stellar-mass black holes in the Milky Way and Large Magellanic Cloud, and a number of the brightest ultraluminous X-ray sources in nearby galaxies. The ultraluminous X-ray sources are restricted to the upper left part of the plot, meaning they are approximately 10 times more luminous than standard stellar-mass black holes but have disks which are 5-10 times cooler. X-ray luminosity scales directly with masss, and accretion disk temperature is inversely related to black hole mass, so these ultraluminous X-ray sources may harbor intermediate-mass black holes (Miller, Fabian, & Miller 2004). Constellation-X will make definitive spectroscopic and timing measurements to strongly confirm or reject the existence of intermediate-mass black holes, dramatically improving on the hints that Chandra and XMM-Newton are providing presently.

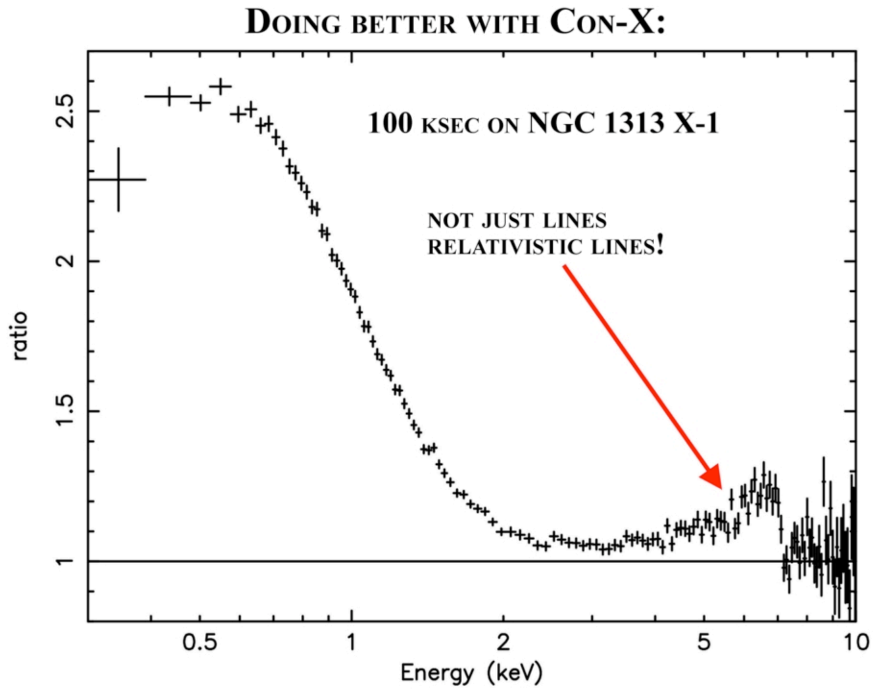

Figure 2: The plot above shows a simulated Constellation X spectrum of the intermediate-mass black hole candidate NGC 1313 X-1, plotted as a ratio to a simple power-law model. A 100 ksec exposure with Constellation-X will clearly reveal the cool accretion disk component first glimpsed with XMM-Newton (Miller et al. 2003). More exciting is the fact that Constellation-X will easily reveal a broad, relativistic Fe K-alpha emission line (extending to low energy from 6.7 keV) from the accretion disk. Detecting such a line will confirm that the soft X-ray emission is due to a disk, will rule-out beaming explanations for the inferred luminosity of the source, and will make it possible to constrain the spin of the black hole. Indeed, Constellation-X will be able to test General Relativity across a broad range in black hole masses.

Relative Impact of Constellation-X:

Local AGN in which reverberation mapping will work:	6-8
Galactic black holes in which GR effects can be probed over a 10 year mission:	10-15
ULXs with some hint of IMBH nature, on which Con-X can be decisive with XMM-like resolution:	20-30

Figure 3: This figure illustrates one view of the comparative impact of Constellation-X with regard to General Relativity and black holes. Relativistic reverberation mapping will incisively probe the Kerr metric, and will be possible in at least 6-8 AGN harboring supermassive black holes. Precision studies of Fe K-alpha emission lines and timing phenomena will be possible in 10-15 stellar-mass Galactic black holes, over the course of a 10-year mission. In 20-30 ULXs, Constellation-X will be able to obtain X-ray spectra and lightcurves that can establish the presence of intermediate-mass black holes - a new class of relativistic object - in these sources.

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